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LETTER

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First prototypes of the new design of the CERN's antiproton production target

Abstract

For antiproton production at CERN, high-energy (26 GeV/c), intense, and short proton beams are impacted into a small rod—target core—made of a dense metal. Temperature rises in the order of 2000°C, and subsequent dynamic stresses of several gigapascals are induced in this rod every time it is impacted by the primary proton beam. Several R&D activities have been launched with the goal of proposing and manufacturing a new design of such device (named AD-Target). A summary of these activities is presented, including the last design stage, which involves the manufacturing and testing of six real-scale prototypes of the new target design. These prototypes (named PROTAD) consist of air-cooled Ti-6Al-4V assemblies filled by matrices made of isostatic graphite or expanded graphite (EG), containing target cores made of small rods with different diameters (from 2 to 10 mm) of multiple grades of Ta, Ta2.5W, and Ir.

1 | INTRODUCTION

Antiproton physics at CERN started in the late 70's and continues until nowadays within the Antiproton Decelerator (AD) facility and subsequent antiproton physics experiments.[1,2] Antiprotons—as well as other charged and neutral particles—are produced out of intranuclear cascade reactions that take place when high-energy protons are impacted with the nuclei of a stationary material (the so-called production target). The AD-Target is specifically designed for antiproton production and consists of a compact device, with a core in the form of rod of a few millimetres in diameter by 5 to 7 cm in length of a high-density refractory metal, onto which proton beams are impacted. This core is embedded in a matrix made of a low-density material such as graphite, which is then inserted in a containing assembly made of Ti-6Al-4V. Inside this assembly, a cooling fluid circulates to evacuate the energy deposited by the primary beam impacts in the target core. The AD-Target design currently in operation dates from the late 80's and consists in a water-cooled assembly with a core matrix made of isostatic graphite of 15-mm external diameter. The core of this design consists of a 3-mm diameter by 55-mm long rod made of iridium.[1] In order to guarantee antiproton physics at CERN for the next decades, a series of consolidation activities in the AD-Target area will take place during CERN's Long Shutdown 2 (2019-2020). Within these activities, a set of new antiproton targets is being designed and manufactured. For arriving to such new design, several R&D activities were launched over the last years, particularly focused in understanding the mechanical response of the target core when subjected to the extreme dynamic stresses induced by the fast and high deposition of energy due to every proton beam impact.[3] These activities are summarized in Section 2 of this paper. The results of such studies lead to the manufacturing of six target prototypes (PROTAD targets), which were tested under proton beam impacts using the CERN's HiRadMat facility.[4] Description of this new design and manufacturing techniques are included in Section 3 of this publication.

2 | PREVIOUS STUDIES LEADING TO THE PROTAD DESIGN

2.1 | Hydrocode simulations of the dynamic response of the target core material

The R&D activities that lead to a new design of the AD-Target started with the use of specific numerical tools (hydrocodes) in order to simulate the core material response at high strain rate and temperature every time it is impacted by the primary proton beam.[5] These numerical tools allow the implementation of advance material models, which take into account the material response beyond plastic deformation and even fracture. In this context, a dynamic characterization of Ir and W at high strain rates and temperatures was performed by means of Split-Hopkinson Pressure bar tests.[6] The parameters of the Johnson-Cook strength model for these materials were extracted from these tests, to be used in the simulations. These numerical studies showed that a high-frequency radial mode is excited in the target core due to the sudden rise of temperature induced by each proton beam impact. The reason for this is that the proton pulse duration (approximately 0.5 μs) coincides with half period of this mode, resulting in a constructive interference between the appearing end-of-pulse tensile waves and the natural radial mode of vibration of the rod. This response subjects the core material to compressive-to-tensile pressures of several gigapascals, above its strength. The simulations also suggest that the containing graphite matrix could be damaged by the generated stress wave propagating from the core.[3] These results encouraged the execution of experimental studies (HiRadMat-27[7] and HiRadMat-42[8] experiments) aiming at validating these simulations and finding a core and matrix material configuration that could withstand these operating conditions.

2.2 | HRMT-27 and HRMT-42 experiments

The aim of the HRMT-27 experiment[7] was to test refractory metals (candidate materials for the future AD-Target design) at equivalent conditions as reached in the AD-Target by using the CERN's HiRadMat facility. The main outcome of this experiment was finding that Ir—the core material of the current design—massively fragments at these conditions, with the subsequent influence in core effective density and potential detriment of the antiproton production yield. Similarly, it happened to most of the tested refractory metals (W, Mo, TZM). Tantalum, on the other hand, did not crack when subjected to conditions similar to those of the current AD-Target. This is attributed to its considerably higher ductility. In addition, the performed hydrocode simulations of Torregrosa et al[5] were validated.[3] Nevertheless, this experiment did not assess the response of Ta when subjected to a high number of proton beam impacts, nor the response of the graphite matrix.

The missing aspects of the HRMT-27 experiment were then addressed by the HRMT-42 experiment[8] by irradiating in HiRadMat the assembly illustrated in Figure 1. This assembly was an upscaled prototype of a proposed new target core and matrix design, consisting in an 8-mm diameter Ta core split into 16-mm long rods surrounded by an EG matrix. The split core is an attempt to reduce the excitation of bending modes observed in HRMT-27 experiment and studied numerically in Solieri.[9] The Ta cores were fit into EG hollow disks and pressed inside a 44-mm diameter Ti-6Al-4V container. The EG matrix was conceived as a solution to the potential solid graphite matrix shattering due to the stress waves arriving from the core and its permanent plastic deformation. The idea was that the compressed EG could accommodate the

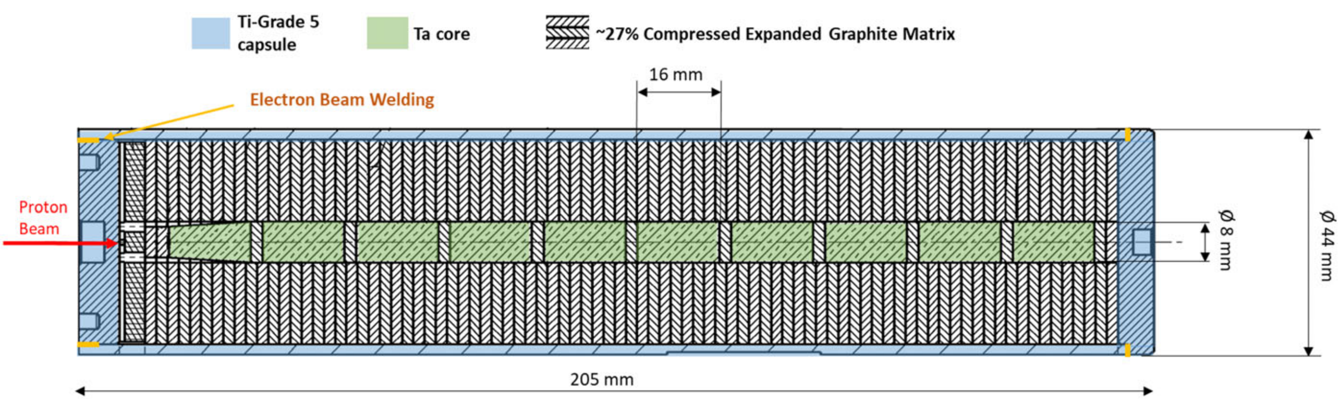

FIGURE 1 Schematics of the HRMT-42 target, first scaled prototype of the core and matrix configuration for a new AD-Target design

radial wave and eventual plastic deformation of the core. The assembly of the HRMT-42 target was carried out using a tailored tooling, which allowed one-stage compression of the EG matrix in the Ti-6Al-4V capsule and the capsule sealing by electron beam welding (EBW) while maintaining the pressure, with the goal of achieving an EG compression ratio of 27%.[8] The outcome of HRMT-42 experiment can be summarized in three points: (1) The irradiation in HiRadMat and Post Irradiation Examinations (PIEs) validated the fact that EG can adapt to the changes in core due to permanent deformation. (2) Splitting the core into short rods avoided excitation of the bending modes observed in the HRMT-27 experiment. (3) A large impact of proton pulses induced a process of fracture of the Ta core not previously observed in HRMT-27, identified as spalling.

The discovery of spalling facture in the HRMT-42 target core led to an increase in its diameter in the PROTAD targets as an attempt to reduce the reached tensile stresses. In addition, it motivated the investigation of the response of Ta with different grain sizes (annealed and not annealed). From the point of view of the return of experience from the assembly procedure of this target, it was observed that the EG compression ratio when performing one-stage compression was considerably non-uniform due to friction with the walls of the Ti-6Al-4V container during compression. The achieved compression ratio of the EG disks in the bottom of the target was just 7%, while 40% in the upper disks was reached.[8] For this reason, a new compression method was proposed for the PROTAD targets (described in Section 3) aiming at achieving a constant compression ratio over the target length.

2.3 | Numerical studies of the core diameter influence on its dynamic response

The numerical studies conducted in Solieri[9] directly led to the chosen core diameters of the PROTAD targets. These studies analysed the excitation of radial, longitudinal, and flexural modes when a proton beam impacts small rods. In this study, hydrocodes and modal analyses were used to study the influence of the target core geometry (in particular diameter and length) in tensile pressures reached. As already introduced in Torregrosa et al,[1] it was shown that the core diameter greatly influences the tensile pressure reached due to interaction of the appearing end-of-pulse tensile waves with the natural radial mode of vibration of the core rods. Due to this effect, rods of 4 mm in diameter were found to be most unfavourable in terms of tensile stress reached. Increasing or reducing the diameter from this dimension decreases the maximum tensile stress reached. Nevertheless, this effect is more pronounced when increasing the diameter. From the point view of the mechanical response of the target core, the most desirable would be to increase the rods diameter as much as possible. However, this is in direct conflict with the physics performance of the target since a higher number of antiprotons is reabsorbed in the periphery of the high-density core. In order to cope with this compromise, the upstream rods of the PROTAD core have larger diameters, as the influence in antiproton reabsorption is lower there, while the core rods diameters are reduced towards the downstream part, where the antiproton reabsorption is more relevant.

3 | THE PROTAD EXPERIMENT DESIGN AND MANUFACTURING

Based on the lessons learned from the studies described, six target prototypes with a similar design as the one shown in Figure 2 have been manufactured. These targets are substantially more compact than the previous design in order to reduce antiproton reabsorption. The new features of the redesigned AD-Target with respect the previous design are the pressurized air-cooling system (instead of water-cooling) and the core and matrix configuration. Each of the six manufactured target prototypes has a different core and matrix configuration. Four targets are based on a matrix of precompressed EG, while the two remaining prototypes are still equipped with matrices made of conventional isostatic graphite as in the old design. In addition, each of the targets is equipped with a different configuration of cores, made of small rods of variable diameters (from 2 to 10 mm) of multiple grades of Ta, Ta2.5W, and Ir, in terms of primary manufacturing method (melted/sintered), annealing, and supplier. Each of the metallic rods of the core surrounded by its containing matrix is designated as a "core module" (Figure 2B). The goal of testing these different configurations is to investigate the possible influence of core microstructure and geometry in the spalling mode of fracture observed in the HRMT-42 experiment. The assembly procedure of the PROTAD targets equipped with EG matrices was also slightly different to the one of the HRMT-42 target. This time, a two-stage compression was carried out. The goal of the implemented changes is to produce an EG matrix with a uniform compression ratio of 33% and to cope with the additional complication of having variable core diameters (a feature not present in the HRMT-42 target as shown in Figure 1). This additional step is especially relevant since after compression of EG to a specific ratio, there is an additional height recovery due to the elastic properties of this material. It was measured that the elastic recovery when compressing to 33% is in

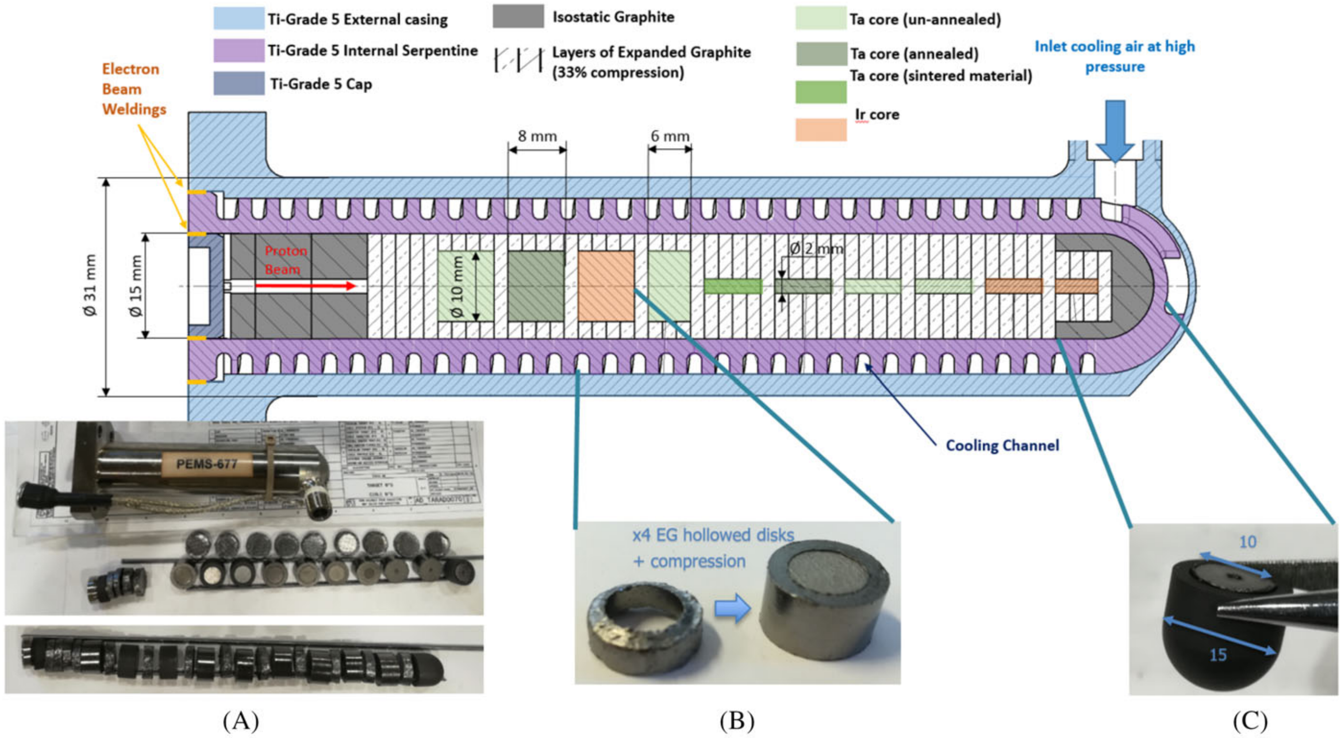

FIGURE 2 Schematics and pictures of one of the PROTAD targets, real-scale prototype of the new AD-Target design, recently irradiated in HiRadMat. This specific target is equipped with an EG matrix and cores of different diameters and grades of Ta and Ir. A, Target components before assembly. B, Precompressed EG matrix around the metallic core. C, Downstream graphite matrix

the order of approximately 6% to 8%, ie, the final compression state when releasing the pressure would be in the order of 26%. This means that, with the variable core diameters, one-way compression as carried out for HRMT-42 target could lead to appearance of gaps between core modules. In order to avoid this, a two-stage method to fill the PROTAD targets was executed. A first-stage involves the precompression of each core module outside the target assembly (using a compression tooling). Second stage consists in the progressive insertion and final compression of each of the precompressed modules in the target cavity, adding uncompressed EG disks between the modules.

The picture presented in Figure 2B shows the outcome of the first compression stage for the specific case of a core module of 10-mm diameter by 8-mm long of Ta, embedded in four EG disks. These disks were compressed around the metallic core up to an approximately 39% compression ratio, in such a way that, after the approximately 6% of "elastic recovery," the EG matrix expands to the same height of the core. Figure 3 illustrates a scheme of the tooling and methodology used for this compression stage, which is composed by four different substeps. This procedure was repeated for all the core modules surrounded by EG matrices in the six target prototypes. Slightly different tooling assemblies were used to compress the EG matrix around the downstream metallic core, which is in turn inserted in a solid graphite semi-spherical tip (Figure 3B).

Figure 4A,B illustrates the second compression stage, in which the different precompressed core modules, together with uncompressed disks—showed outside the target in the picture of Figure 2A—are progressively inserted and compressed in the target cavity. The insertion and compression of these modules with the uncompressed disks were carried out in a gradual manner, ie, no more than two modules are inserted at once. After the insertion of each module, the presser compresses them (especially the uncompressed EG disks between them) to the corresponding height in which all the EG disks have a 33% compression ratio. Elastic recovery during this step is significantly reduced due to friction with the walls of the radially expanded EG disks. Once the target has been completely filled, the Ti-6Al-4V lid is inserted in the target cavity. Then the last compression stage (to cope with the elastic recovery of the last "core modules" inserted) was carried out by using a bolted piece at the upstream flange of the target (Figure 4D). This bolted piece was used to level the lid to the target assembly. In this way, the Ti-6Al-4V lid was electron-beam welded to seal the target while maintaining its content under compression. Figure 4E shows a picture of the six manufactured targets before installation in the experimental set-up to expose them to proton beam impacts in the HiRadMat facility.

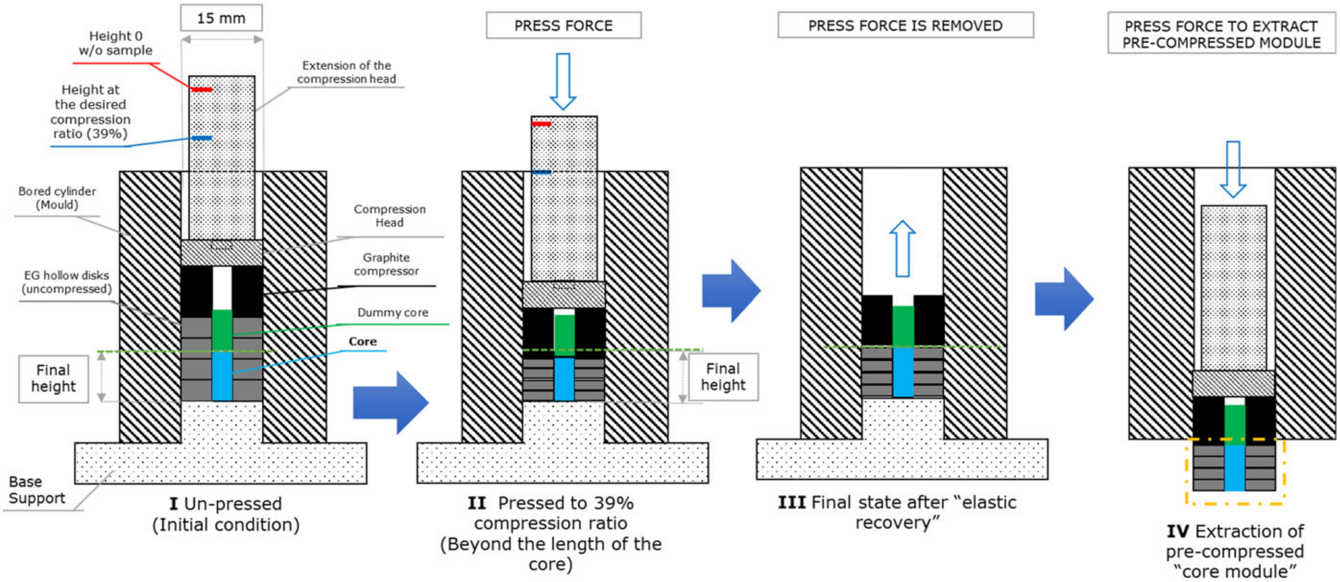

FIGURE 3 Scheme of the methodology and tooling used in first precompression stage of the EG matrices around the metallic cores of the target

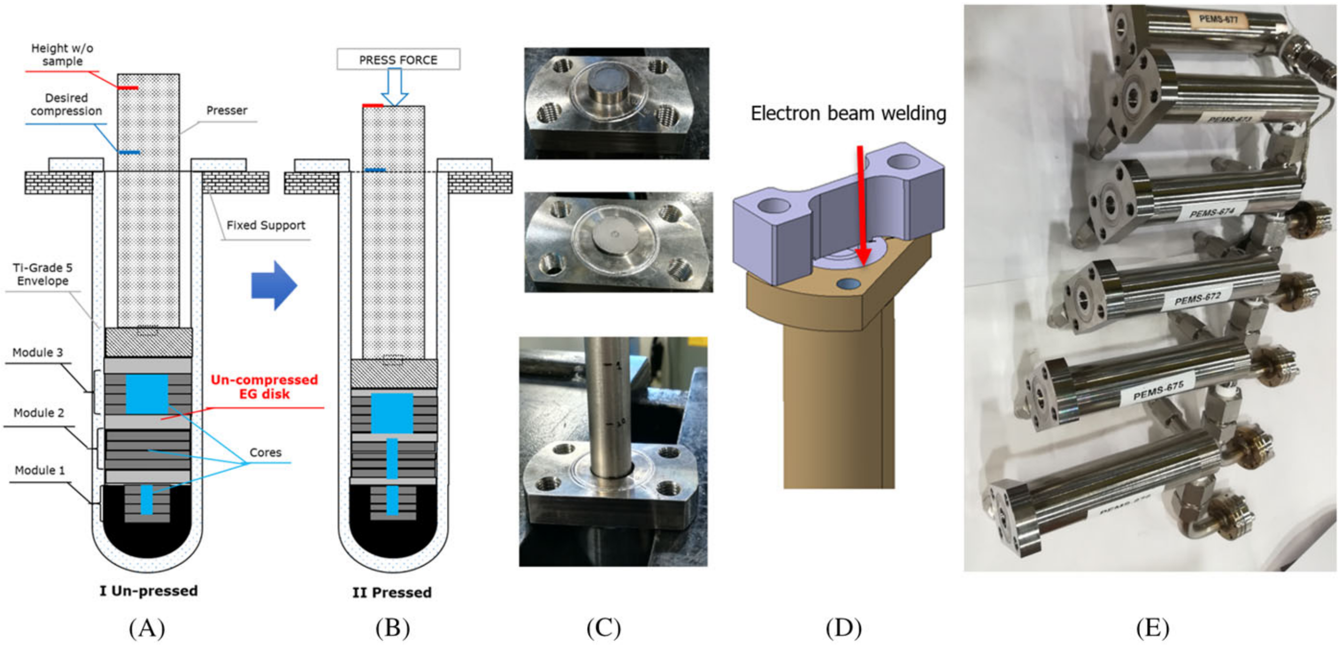

FIGURE 4 A-D, Scheme of the methodology and pictures of the second stage of the EG matrices consisting in insertion and compression inside the target cavity. E, Six manufactured targets before installation in the experimental set-up

4 | CONCLUSIONS AND FURTHER PERSPECTIVES

The testing in HiRadMat of the PROTAD targets will allow a direct comparison between the performance of EG and conventional isostatic graphite (from the point of view of the core matrix), as well as to assess the proton beam induced damage in the core made of different refractory metals. This assessment will be based on the fact that each core rod in a given longitudinal position within each target is exposed to equivalent conditions in terms of sudden depositions of energy by the impacted proton beam. Hence, the core materials and geometries within these modules in the targets have been selected accordingly to extract the maximum information from the comparisons of the response at the same loading conditions. PIEs after PROTAD targets opening foreseen in 2019 will reveal which core material and geometry behaves better and provide a last input of the most performant core configuration, which will be included the final AD-Target new design, to start in operation in 2021.

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CONFLICT OF INTEREST

Authors declare no conflict of interests.

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